CHAPTER

9

BLUETOOTH LOW ENERGY DEMODULATOR ARCHITECTURES

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9.1 INTRODUCTION

The popularity of the Internet of Things (IoT) has increased the demand for a wireless standard for short-distance data transmission that consumes little energy (Mak et al., 2007). Bluetooth Low Energy (BLE) or Bluetooth 4.0 is a protocol for occasionally transmitting a small amount of data while being powered by a small battery that can last for months. BLE employs Gaussian Frequency Shift Keying (GFSK) as a modulation standard and runs at 2.4 GHz ISM radio band with a data rate of 1 Mbit/s.

The process of retrieving original information-bearing signals from a carrier wave is referred to as demodulation. The demodulator can be implemented as an electrical circuit or as a software-defined radio application. In this chapter, we present circuit topologies (rather than software) for BLE demodulators, such as the amplitude Analog-to-Digital Converter (ADC) demodulator, the Limited based demodulator, and the Phase Domain ADC (Ph-ADC) demodulator, as they have been primarily explored in the literature. These architectures are based on the Zero-IF and Low-IF receiver architectures, which have been determined to be the most appropriate for BLE due to their simple structure and low power consumption (Mak et al., 2007). Before delving into these designs, the fundamental BLE specification of the demodulator will be covered.

9.2 DEMODULATOR SPECIFICATION

This section discusses the BLE specifications for demodulators such as GFSK modulation, frequency offset, synchronization, Bit Error Rate (BER) and receiver's sensitivity.

9.2.1 Modulation Specification

The BLE standard uses the 2.4 GHz ISM band and consists of 40 channels whereby each channel occupies 2 MHz bandwidth. In terms of modulation standard, GFSK is employed instead of Frequency Shift Keying (FSK) so that magnitude of the side lobe in the frequency domain can be reduced as shown in Figure 9.1. The reduced sidelobe reduces interference to neighboring channels (Nsour et al., 2014). This is because the Gaussian filter smoothest out the sharp transition of '0 to 1' and '1 to 0'. However, this comes at the cost of Inter-Symbol Interference (ISI) where demodulation is more prone to error (Nsour et al., 2014).

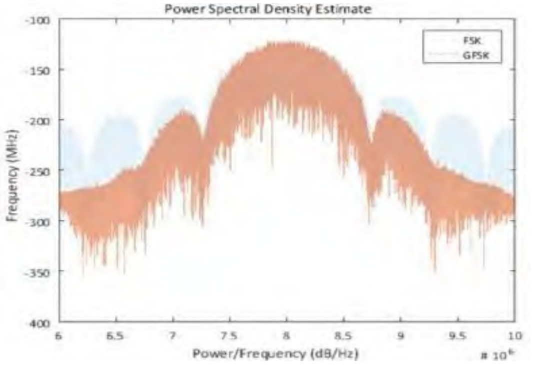

Figure 9.1 The frequency spectrum of modulated signals for frequency shift keying and gaussian frequency shift keying with a bandwidth bit period product, BT = 0.5 at the center frequency of 8 MHz

9.2.2 Frequency Shifting and Offset

In Bluetooth Low Energy (BLE), digital information is modulated at 1 Mbit/s with the modulation index of $0.45 \leq m \leq 0.55$, whereby,

$$m = \frac{2\Delta f}{f_m} \tag{9.1}$$

Where Δf is the frequency deviation from the center frequency and fm is the bit rate. The Δf value is dependent on the neighbouring bit value due to Inter-Symbol Interference (ISI) caused by Gaussian filter.

As shown in Figure 9.2, there are 3 different levels of frequency deviation from center frequency which are Δf_1, Δf_2 and Δf_3 and their respective neighboring bit conditions are tabulated in Table 9.1. The three different levels of frequency deviation also elaborate the BLE specification whereby Δf during "01010101" sequence shall be at least 80% of "11110000" sequence. In other words, Δf_3 shall be no smaller than 80% of Δf_1. Other than that, the crossing at the zero shall fall within ± 1/8 of the symbol period during the bit transition from '0 to 1' or '1 to 0'.

Table 9.1 Δf value according to neighbouring bits due to inter-symbol interference

bit_{i-1}	bit_i	bit_{i+1}	Δf
0	1	0	$+\Delta f_3$
0	1	1	$+\Delta f_2$
1	1	0	$+\Delta f_2$
1	1	1	$+\Delta f_1$
0	0	0	$-\Delta f_1$
1	0	0	$-\Delta f_2$
0	0	1	$-\Delta f_2$
1	0	1	$-\Delta f_3$